XXVI. *On the Influence of Atmospheric Pressure upon some of the Phenomena of Combustion.* By Dr. E. FRANKLAND, *F.R.S.*

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IN his classical researches upon flame, DAVY mentions the influence which compression and rarefaction exert upon combustion in atmospheric air. Speaking of his experiments with compressed air, the performance of which presented considerable difficulties, he says*, "They show sufficiently that (for certain limits at least) as rarefaction does not diminish considerably the heat of flame in atmospherical air, so neither does condensation considerably increase it; a circumstance of great importance in the constitution of our atmosphere, which at all heights or depths at which man can exist, still preserves the same relations to combustion." His attention was also arrested by the light evolved under similar circumstances, although this phase of the subject does not seem to have attracted more than his cursory attention, and he does not appear to have made any exact quantitative determinations of the rate of increase or diminution of the light of combustion. In reference to this point he says†, "Both the heat and light of the flames of the taper, of sulphur, and of hydrogen were increased by acting on them by air condensed four times; but not more than they would have been by an addition of $\frac{1}{5}$ of oxygen." And again‡, "The intensity of the light of flames in the atmosphere is increased by condensation and diminished by rarefaction, apparently in a higher ratio than their heat, more particles capable of emitting light exist in the denser atmospheres, and yet most of these particles in becoming capable of emitting light, absorb heat; which could not be the case in the condensation of a pure supporting medium."

M. TRIGER, a French engineer §, records some observations on combustion in compressed air, which were made during some engineering operations of a peculiar kind, carried on in working a bed of coal lying beneath the alluvium on the banks of the river Loire. A stratum of quicksand from 59 to $65\frac{1}{2}$ feet thick had to be penetrated; and it was consequently necessary to find some means of excluding the quicksand and water, which it was found impossible to keep out by the ordinary coffer-dams. To overcome this difficulty, M. TRIGER ingeniously employed stong wrought-iron cylinders about $3\frac{1}{4}$ feet in diameter, open below and closed at top. These were gradually sunk in the quicksand, whilst the air inside them was compressed to the necessary extent to exclude the outer semifluid matter. The workmen labouring within these cylinders were exposed to a pressure of about three atmospheres; and it was observed that the candles, by which they

* Philosophical Transactions for 1817, p. 65.

† Ibid. p. 64.

‡ Ibid. p. 75.

§ Ann. de Chimie et de Physique, 3 sér. tome iii. p. 234, 1841.

were lighted, burnt with much greater rapidity than at ordinary atmospheric pressure. Respecting this rapid combustion, M. TRIGER says, "A la pression de trois atmosphères, cette accélération devient telle que nous avons été obligés de renoncer aux chandelles à mèches de coton pour les remplacer par des chandelles à mèches de fil. Les premières brulaient avec une telle rapidité qu'elles duraient à peine un quart d'heure, et elles répandaient en outre une fumée intolérable."

An observant officer of artillery stationed in India, Quartermaster MITCHELL, found that the time of burning of the fuses of shells was considerably increased from the diminution of atmospheric pressure at elevated stations. To the results of his experiments I shall presently have to refer in detail.

Finally, J. LE CONTE*, in his interesting memoir on the influence of solar light on combustion, expresses the following opinion, with reference to the observations of DAVY, TRIGER, and MITCHELL: "Thus a variety of well-established facts concur in fortifying the conclusions to which we are led by *à priori* reasoning, namely, that the process of combustion is *retarded* by diminution of the density of the air, whilst it is accelerated by its condensation." M. LE CONTE did not himself make any experiments on the influence of atmospheric pressure on the rate of combustion.

Such was the state of knowledge and opinion regarding the influence of atmospheric pressure upon the heat and light of combustion, when in the autumn of 1859, whilst accompanying Dr. TYNDALL to the summit of Mont Blanc, I undertook some experiments on the effect of atmospheric pressure upon the rate of combustion of candles.

I. INFLUENCE OF ATMOSPHERIC PRESSURE ON THE RATE OF COMBUSTION.

α. Of Candles.

In the experiments just alluded to, six stearin candles were first burnt for one hour at Chamonix, the amount of stearin consumed being carefully determined for each candle: the same candles were afterwards burnt for one hour, carefully protected from currents of air, in a tent on the summit of Mont Blanc, the consumption of stearin being again ascertained. The following results were obtained:—

Number of Candle.	At Chamonix. Barometer 26·4 inches, temp. 21°·5 C. Stearin consumed in one hour.	Summit of Mont Blanc. Temperature of air in tent 0°·5 C. Stearin consumed in one hour.
	grammes.	grammes.
1.	9·2	8·7
2.	9·9	9·5
3.	9·2	9·2
4.	10·4	8·8
5.	9·5	9·3
6.	9·2	9·0

* SILLIMAN'S American Journal of Science and Arts [2] xxiv. 317.

These numbers give the following average rates of combustion:—

At Chamonix .... 9·6 grms. stearin per hour.
Summit of Mont Blanc .... 9·1 grms. stearin per hour.

Or, omitting the fourth candle, which obviously gave abnormal results, the following would be the average rate of combustion:—

At Chamonix .... 9·4 grms. stearin per hour.
Summit of Mont Blanc .... 9·2 grms. stearin per hour.

This close approximation of the two results under such widely different atmospheric pressure, goes far to prove that *the rate of combustion of candles is entirely independent of the density of the air*, the slight discrepancy being probably attributable to the difference (21° C.) of atmospheric temperature in the two series of experiments. It is impossible to repeat these determinations in a satisfactory manner with artificially rarefied atmospheres, owing to the heating of the apparatus which surrounds the candle, and the consequent guttering and unequal combustion of the latter. But in an experiment with a sperm candle, which was burnt first in air under a pressure of 28·7 inches of mercury, and then in air at 9 inches pressure, other conditions being as similar as practicable in the two experiments, the consumption of sperm was found to be,—

At pressure of 28·7 inches . . . . 7·85 grammes of sperm per hour.
At pressure of 9·0 inches . . . . 9·10 grammes of sperm per hour.

This experiment, unsatisfactory as it was in several respects, tends to confirm, for higher degrees of rarefaction, the result previously obtained.

β. *Of Time-fuses.*

In a letter dated January 6th, 1855, an extract from which appeared in the 'Proceedings of the Royal Society *,' Quartermaster MITCHELL communicated the results of a series of carefully conducted experiments, proving that the rate of combustion of the fuses of shells was subject to considerable retardation, which he attributed to the diminution of atmospheric pressure at elevated stations, causing a more scanty supply of oxygen. The following is a short statement of the results of these experiments, in which three-inch fuses were burnt under different atmospheric pressures:—

	Height of barometer at 0° C.	Elevation above sea-level.	Time of burning.
	inches.	feet.	seconds.
1. Average of 6 experiments ..	29·61	....	14·25
2 Average of 6 experiments ..	26·75	3000	15·78
3 Average of 4 experiments ..	23·95	6500	17·10
4 Average of 2 experiments ..	22·98	7300	18·125

* Vol. vii. p. 316.

Comparing the amount of retardation with the corresponding reduction of pressure, we have the following results:—

Numbers of experiments between which comparison is made.	Diminution of pressure.	Retardation of combustion.
	inches.	seconds.
1 and 2	2·86	1·53
2 and 3	2·80	1·32
3 and 4	·97	1·025

Although these results, as I shall presently endeavour to show, are perfectly compatible with those obtained with candles under similar circumstances, yet the subject seemed to me of sufficient technical importance to warrant a repetition and extension of these experiments in artificially rarefied air. For this purpose a large iron cylinder was connected on the one hand with an air-pump, and on the other with a piece of gas-pipe 6 feet long and 4 inches internal diameter, the opposite end of the pipe being furnished with an arrangement by which the end of the fuse to be ignited could be introduced air-tight within the pipe, whilst the closed end of the fuse projected about 2 inches into the external air. The fuses were ignited at a given instant by a voltaic arrangement, consisting of ten cells of GROVE'S battery, an instantaneous contact maker, and a piece of thin platinum wire which was inserted into the priming of the fuse. In order to ascertain with precision the moment when the deflagration was finished, the lateral hole at the posterior end of the fuse was bored through to the opposite side: a piece of thread was passed vertically through this aperture, and secured above to a convenient support, whilst an iron ball was affixed to its lower extremity at a distance of a few inches above an iron plate, upon which the ball fell when the fire reached the thread, thus indicating the moment when, under ordinary circumstances, the fire of the fuse would be communicated to the contents of the shell. The pressure was indicated by a mercurial gauge inserted into the gas-pipe.

The experiments were made with 6-inch fuses (for which I was indebted to the kindness of Mr. ABEL of the Woolwich Royal Arsenal), in the following manner. The fuse being inserted into the end of the gas-pipe, and the necessary degree of exhaustion in the iron cylinder and pipe having been obtained, the fuse was ignited at a given signal. During the continuance of its deflagration, an assistant worked the air-pump so as to prevent any great rise in pressure, whilst another observed the vacuum-gauge at the moment when the iron ball dropped. The mean between the pressure at the commencement of the deflagration, and that at the end, was assumed to be the mean pressure under which the fuse had been burnt; but it is obvious that this assumed mean pressure can only be approximative, although the gauge fell very regularly and gradually during the continuance of the deflagration.

The following results were obtained:—

I. At a barometrical pressure of 30·4 inches, fuse No. 1 burnt 31 seconds*.

* The first three fuses were burnt in the open air, but the arrangements for their ignition and for determining the cessation of combustion, were the same as in the other determinations.

II. At a pressure of 30·4 inches, fuse No. 2 burnt 30 seconds.
III. At a pressure of 30·4 inches, fuse No. 3 burnt 30 seconds.
IV. At the mean pressure of 28·4 inches, fuse No 4 burnt 32 seconds.
V. At the mean pressure of 28·1 inches, fuse No. 5 burnt 32·5 seconds.
VI. At the mean pressure of 25·55 inches, fuse No. 6 burnt 35 seconds.
VII. At the mean pressure of 25·85 inches, fuse No. 7 burnt 34·5 seconds.
VIII. At the mean pressure of 22·35 inches, fuse No. 8 burnt 38 seconds.
IX. At the mean pressure of 22·55 inches, fuse No. 9 burnt 37·5 seconds.
X. At the mean pressure of 19·9 inches, fuse No. 10 burnt 42 seconds.
XI. At the mean pressure of 19·4 inches, fuse No. 11 burnt 41 seconds.
XII. At the mean pressure of 16·15 inches, fuse No. 12 burnt 46 seconds.
XIII. At the mean pressure of 15·75 inches, fuse No. 13 burnt 45 seconds.

It will be seen, from an inspection of the above numbers, that, after the three first experiments at atmospheric pressure, an attempt was made to burn two fuses at the same pressure, but owing to the gauge sinking to the extent of about two inches during the deflagration, the mean pressures at which each pair of fuses were burnt never exactly coincided. For the purpose of comparison, however, it will be convenient to take the mean both of the pressures and times of burning of each pair, and to express the results as follow :—

Average pressure, in inches of mercury.	Average time of deflagration of 6-inch fuse.	Increase of time of burning over preceding observation.	Reduction of pressure corresponding with increase of time.	Increase of time for each diminution of 1 inch pressure.
	seconds.	seconds.	inches.	seconds.
30·40	30·33			
28·25	32·25	1·92	2·15	·893
25·70	34·75	2·50	2·55	·980
22·45	37·75	3·00	3·25	·925
19·65	41·50	3·75	2·80	1·339
15·95	45·50	4·00	3·70	1·081

There are here evident indications of the rate of retardation being somewhat greater at low than at comparatively high pressures; but, neglecting these indications, the above numbers give 1·043 second as the average retardation in a six-inch or thirty-seconds fuse for each inch of mercurial pressure removed. This result agrees closely with that obtained by Quartermaster MITCHELL, if we except those fuses which he burnt at the greatest altitude, and in referenee to which some error must obviously have crept in, either as regards the altitude of the station where the fuses were burnt, or the duration of their combustion. The latter source of error is perhaps rendered less improbable, from the fact that only two experiments were made at the greatest altitude, whilst six were performed at two, and four at the third of the remaining stations. The following Table shows Mr. MITCHELL's results, uniformly with those in the last Table. The fuses which he employed being fifteen-seconds or three-inch ones, I have multiplied their

times of combustion by two, in order to bring them into comparison with the six-inch fuses which were used in my experiments:—

Pressure in inches of mercury.	Average time of combustion of 6-inch fuse.	Increase of time of combustion over last observation.	Reduction of pressure corresponding to increase of time.	Increase of time for each diminution of 1 inch pressure.
	seconds.	seconds.	inches.	seconds.
29·61	28·50			
26·75	31·56	3·06	2·86	1·070
23·95	34·20	2·64	2·80	·943
22·98	36·25	2·05	·97	2·113

Here, omitting the last determination as abnormal, we have the average retardation, in the combustion of a six-inch fuse, equal to 1·007 second for each diminution of one-inch mercurial pressure, which coincides almost exactly with the number (1·043) deduced from my own experiments.

The results of both series of observations may therefore be embodied in the following law:—*The increments in time are proportional to the decrements in pressure.*

For all practical purposes the following rule may be adopted:—*Each diminution of one inch of barometrical pressure causes a retardation of one second in a six-inch or thirty-second fuse.* Or, *each diminution of atmospheric pressure to the extent of one mercurial inch increases the time of burning by one-thirtieth.*

This retardation in the burning of time-fuses by the reduction of atmospheric pressure, will probably merit the attention of artillery officers. These fuses have hitherto been carefully prepared so as to burn, at Woolwich, a certain number of seconds, and the perfection with which this is attained is highly remarkable; but such time of combustion at the sea-level is no longer maintained when the fuses are used in more elevated localities. The ordinary fluctuations of the barometer in our latitude must render the rate of combustion of these fuses liable to a variation of about ten per cent. Thus a fuse driven to burn 30 seconds when the barometer stands at 31 inches, would burn 33 seconds if the barometer fell to 28 inches. The height to which a shell attains in its flight must exert an appreciable influence upon the burning of its time fuse; to a far greater extent, however, must the time of combustion be affected by the position of the fuse during the flight of a rifled shell: as in these projectiles the fuse always precedes the shell, the time of burning must obviously be very much shorter than when the shell and fuse are at rest. In an ordinary shell which rotates upon a horizontal axis, the alternate compression and rarefaction of the air at the mouth of the fuse, although tending to compensate each other, will still leave a considerable balance of compression, which must cause a marked retardation in the rate of burning.

The apparently opposite conclusions to which we are led as regards the influence of atmospheric pressure upon the *rate* of combustion, by the experiments upon candles on the one hand and upon time-fuses on the other, are by no means irreconcileable; in

fact, an examination into the conditions of combustion in the two cases scarcely leaves room for the expectation of any other result.

In the combustion of a candle, the radiant heat from the flame first melts the combustible matter in the capsule at the base of the exposed portion of the wick; the capillary action of the latter then elevates the liquefied wax, tallow, or spermaceti into the upper part of the wick, where it is exposed to a temperature which effects its volatilization and decomposition. It is thus evident that the rate of combustion, or at all events the rate of consumption of the combustible matter of the candle, is entirely dependent upon the capillarity of the wick, provided that the radiant heat from the flame is sufficient to keep up a supply of liquefied combustible matter at the base of the wick, and that the temperature of the flame is high enough to volatilize this matter on its arrival near the apex of the cotton. Now, as capillary attraction is not altered by variations of atmospheric pressure, and as the temperature of the flame is, as will be shown below, almost entirely independent of the same influence, a diminution in the consumption of combustible matter could only arise from the amount of radiant heat striking the capsule at the base of the wick being insufficient to keep up a supply of melted combustible matter equal to the capillary demands of the wick. There can scarcely be a doubt that the amount of heat radiated from a given area of the lower surface of the flame is diminished by rarefaction, owing to the decreasing luminosity of the flame: nevertheless this diminution is compensated by the increased flame surface, the radiant heat from which strikes the capsule when the flame becomes enlarged by rarefaction. Whether this compensation be complete or not is of little importance, since observation shows that, even at the highest degrees of rarefaction, a sufficient amount of heat reaches the capsule to keep up an abundant supply of liquefied combustible matter.

We have therefore no ground for any *à priori* assumption that the combustion of candles ought to go on at a decreased rate in rarefied air; in fact there is one consideration which might lead to the opposite opinion; it is this,—the rapidity of the consumption of a candle obviously depends upon the amount of liquefied wax, &c. which passes up its wick in a given time: this amount is determined, up to a certain maximum limit, by the rapidity with which it is got rid of at the upper portion of the capillary tubes where it is volatilized by the heat of the flame. Now, as the rapidity of volatilization is known to be increased by a reduction of pressure, it follows that a larger amount of the combustible would be thus removed from the upper portion of the wick in rarefied than in compressed air. Nevertheless this influence of reduced pressure must be very small in the case of bodies possessing such high boiling-points as tallow, wax, &c., and hence its influence upon the rate of combustion in rarefied air cannot be perceived.

Opposed to the above facts and considerations stands the observation of M. TRIGER, that candles burn much more rapidly in air compressed three times than in air at the ordinary pressure. This discrepancy, the cause of which can now only be conjectured, may perhaps reside in some of the circumstances, described above, under which the experiments were made. The constant supply of compressed air to a chamber such as that

in which the candles were burnt, must have occasioned a comparatively high temperature in the atmosphere of the chamber, necessarly causing the candles to gutter. Further, the very imperfect combustion which a candle undergoes at this high pressure would have a tendency to increase the size of that portion of the wick situated within the flame, and which constitutes the surface from which the evaporation of the combustible proceeds. Both these circumstances would, I conceive, practically tend greatly to shorten the time during which a candle would burn, which was precisely the circumstance that alone attracted M. TRIGER'S attention, no quantitative determinations of the weight of combustible matter *actually consumed* having been made.

In the deflagration of time-fuses, the conditions are obviously very different. Here the combustible matter never comes into contact with atmospheric oxygen until it has left the fuse-case; unlike the candle, the composition contains within itself the oxygen necessary for combustion, and a certain degree of heat only is necessary to bring about chemical combination. If this heat were applied simultaneously to every part of the fuse-composition, the whole would burn almost instantaneously. This sometimes approximately occurs, when, by the expansion of the wooden case into which the composition is rammed, a slight space is formed between the case and its contents, thus allowing the deflagration to propagate itself between the case and the composition. Under such circumstances the fuse burns with explosive rapidity; and probably the occasional bursting of shells before, or immediately after leaving the guns, may be due in some cases to this cause. Under normal circumstances, however, the fuse burns only at a disc perpendicular to its axis; and the time occupied in its deflagration necessarily depends upon the rapidity with which each successive layer of composition is heated to the temperature at which chemical combination takes place. This heat, necessary to deflagration, is evidently derived from the products of the combustion of the immediately preceding layer of composition; and the amount of heat thus communicated to the next unburnt layer must depend, in great measure, upon the number of particles of these heated products which come into contact with that layer. Now, as a large proportion of these products are gaseous, it follows that, if the pressure of the surrounding medium be reduced, the number of ignited gaseous particles in contact at any one moment with the still unignited disc of composition will also be diminished. Hence the slower rate of deflagration in rarefied air.

II. INFLUENCE OF ATMOSPHERIC PRESSURE ON THE LIGHT OF COMBUSTION.

a. Influence of Rarefaction.

In burning candles upon the summit of Mont Blanc, I was much struck by the comparatively small amount of light which they emitted. The lower and blue portion of the flame, which, under ordinary circumstances, scarcely rises to within a quarter of an inch of the apex of the wick, now extended to the height of one-eighth of an inch above the cotton, thus greatly reducing the size of the luminous portion of the flame.

On returning to England, I repeated the experiment under circumstances which

enabled me to ascertain, by photometrical measurements, the extent of this loss of luminosity in rarefied air. The result proved that a great reduction in illuminating effect ensues when a candle is transferred from air at the ordinary atmospheric pressure to rarefied air. At the same time remarkable changes in appearance occur in the flame itself, especially at high degrees of rarefaction. During the diminution of pressure down to half an atmosphere, the chief alteration is the gradual invasion of the upper and luminous portion of the flame, by the lower blue and non-luminous part. As the pressure sinks towards 10 inches of mercury, the retreat of the luminous portion of the flame towards the apex goes on uninterruptedly, but the shape and colour of the flame also begin to undergo very remarkable alterations; the summit becomes more and more rounded, until at 10 inches pressure the flame assumes nearly the form of an ellipse, whilst the blue portion, which now comprises nearly the whole flame, acquires a peculiar greenish tint. Finally, at 6 inches pressure the last trace of yellow disappears from the summit of the flame, leaving the latter an almost perfect globe of the peculiar greenish-blue tint above mentioned. Just before the disappearance of the yellow portion of the flame, there comes into view a splendid halo of pinkish light, forming a shell half an inch thick around the blue-green nucleus, and thus greatly enlarging the dimensions of the flame. The colour of this luminous shell closely resembles that first noticed by GASSIOT in the stratified electrical discharge passing through a nearly vacuous tube containing a minute trace of nitrogen. The colour thus imparted to the electrical discharge undoubtedly constitutes the most delicate test of the presence of nitrogen. In both cases I believe the coloured light to be due to incandescent nitrogen. Under a pressure of 4·6 inches of mercury, a small gas-flame burning in the chimmey *b*, Plate XVIII. fig. 1, nearly fills the latter with the pinkish glow just mentioned, which extends to a height of nearly 3 inches above the true flame, forcibly reminding the observer of the electrical discharge through a nearly vacuous tube. The gas-flame did not manifest any tendency to extinction at this low pressure.

In attempting photometrical determinations with candles, it was found that, owing to the irregularities of combustion already noticed, no satisfactory quantitative experiments could be made in artificially rarefied air. Oil-lamps proved also equally unsuitable, owing to the gradual ascent of the base of the flame towards the apex of the wick, by which the size of the flame and the hourly consumption of oil were greatly diminished. Recourse was therefore had to coal-gas, which, although liable to certain minor disturbing influences, yet yielded results, during an extensive series of experiments, exhibiting sufficient uniformity to render them worthy of confidence.

Fig. 1, Plate XVIII., represents the arrangement of the apparatus employed. A is a governor into which the gas was first led, and whence it issued through a T-piece, one branch of which led to the jet B, which I will call *the standard flame*, whilst the other communicated with the test-meter C supplying a jet D, which may be conveniently termed *the experimental flame*: thus the delivery of gas of uniform pressure, at the two stopcocks regulating the supply to the two flames, was secured. The standard flame was shielded

from currents of air by a cylindrical glass shade. The vessel or receiver, in which the experimental flame was made to burn under different atmospheric pressures, consisted of a glass cylinder 12 inches high and $4\frac{1}{2}$ inches in diameter, welted and ground at both ends, which could be closed air-tight by the ground cast-iron plates *a a*, between which and the ends of the cylinder collars of leather were introduced, so as to distribute more evenly the pressure exerted by the nuts and screws of the three steel rods binding together the upper and lower plates. *b* is a glass chimney contracted at top and cemented with plaster of Paris into the stopcock *c*, which opens the communication for the exit of the products of combustion; *d* is a similar stopcock inserted into the under plate, for the admission of air into the cylinder. The gas-delivery tube *e* passes air-tight through a stuffing-box *f* in the cover of the cylinder, and was most carefully united with the exit-tube of the meter so as to exclude the admission of any trace of air during the experiments, and especially whilst the gas was being consumed under reduced pressure.

The atmosphere within the glass cylinder D could be uniformly maintained at any pressure, from that of the atmosphere downwards, by means of the air-pump E and the reservoir F. The latter was constructed of wrought iron, and, having a capacity of $2\frac{3}{4}$ cubic feet, served to maintain a very constant pressure unaffected by the intermittent action of the air-pump. The pressure in the reservoir, and consequently in the glass cylinder D, was indicated by the gauge G, which was usually worked with mercury, but occasionally, as described below, with water. H H is a Bunsen's photometer, by means of which, the relative intensity of the light of the standard flame and of the experimental flame was determined. The moveable paper disc *g* was protected from diffused light by the cylinder *h h*, so placed that the line joining the two flames passed through its axis. This cylinder was pierced with two apertures at opposite sides,—the one in front (shown in the figures) allowing the observer simultaneously to see the reflected images of both sides of the disc in two mirrors (not shown in the figure) placed at a proper angle behind the opposite aperture.

Such is a general outline of the arrangement of the apparatus used; but the following additional particulars may serve to illustrate more fully the mode of working, and also to explain some of the details of the figure not yet alluded to. The test-meter C was constructed in the usual manner, so as to show by observations of one minute's duration, the rate of consumption per hour; but, in order to ensure greater accuracy, these observations were always extended over a space of at least five minutes, and were repeated at intervals during the course of the determinations at each particular pressure. In order to have the rate of admission of gas to the experimental flame perfectly under control, a micrometer stopcock (*i*) was inserted in the exit-tube of the meter. Just above the internal orifice of the stopcock *d*, was placed a circular disc, so as to prevent the current of air from impinging upon the experimental flame; by this arrangement the latter always burnt with perfect steadiness. It is well known that the illuminating effect of a gas-flame depends very considerably upon the velocity of the current of air in which it burns, and that the maximum illuminating effect is always produced when

the velocity of the current of air is only just sufficient to prevent the escape of unconsumed fuliginous matter; in other words, a maximum of light is obtained from a gas-flame, other things equal, when that flame is maintained just below the *smoking-point*. This condition of maximum luminosity was carefully secured in all the following determinations, by regulating, by means of the stopcock *d*, the admission of external air, and thereby the velocity of the current in the chimney *b*, the cock *c* being wide open. When, however, the experimental flame was burning at atmospheric pressure, the cock *d* was removed, leaving a large aperture for the admission of air, whilst the current through the chimney was regulated by the cock *c*. The extremity of the gas-delivery tube *e* was narrowed to a circular aperture 1·5 millimetre in diameter (about $\frac{1}{17}$th inch), thus forming a burner of such magnitude as not only to prevent the gas from being discharged from *e* with more than the smallest possible pressure, but also to render the difference of pressure between the gas in *e* and the air in the glass cylinder practically the same in all the observations. In the early stages of the experiments considerable annoyance was experienced by the water produced in the combustion condensing in the tubes leading from the chimney *b* to the reservoir F, whilst the cock *c* and the caoutchouc connector between *c* and *k* became inconveniently heated. These difficulties were removed by enclosing the caoutchouc joint with a tin jacket (*l*), which was kept filled with hot water, and by providing two double-necked bottles (only one of which, *m*, is shown in the figure), immersed in vessels of cold water, for the completion of the refrigeration and the collection of the condensed water. *m* was conveniently connected with F, and the latter with the air-pump, by means of vulcanized india-rubber tubing of sufficient substance to resist compression, when rendered nearly vacuous internally.

Each series of experiments was made in the following manner:—The standard flame B was lighted, and its rate of consumption regulated to about ·6 or ·7 cubic foot per hour. The absolute amount of gas consumed by this flame was obviously not material, provided that its rate of consumption and conditions of combustion did not vary during the continuance of any one series of experiments. This constancy in the rate and conditions of combustion was secured by the governor A. The cock *c* being closed, and the pressure in F reduced to about 6 inches of mercury, the cock *d* was removed, *c* slightly opened, and the experimental flame ignited by the introduction of a small taper through the aperture from which *d* had been removed: the latter cock was then replaced, and gradually turned so as to cut off all but the necessary supply of air, whilst *c* was at the same time gradually opened so as to equalize the pressure in the glass cylinder and in F. With this diminution of pressure in the glass cylinder it was of course necessary simultaneously to reduce the size of the aperture through which the gas passed from the meter to the burner; and this was effected by the micrometer cock *i*. The pressure in F was now allowed to rise until it reached the lowest point at which a series of observations was to be made: at this point it was then maintained constant by the steady working of the air-pump. The consumption of gas in the experimental flame having been now accurately adjusted to ·65 cubic foot per hour, and all extraneous light excluded

from the room, a preliminary observation was made of the illuminating power of the experimental flame as compared with the standard. Owing to the gradual heating of the apparatus surrounding the experimental flame, the temperature, and consequently the luminosity of the latter, underwent a gradual and not unimportant increase, which continued for about an hour, when the illuminating power became perfectly constant. As soon as this constancy of light had been obtained, twenty observations of the illuminating power were made. The pressure in F was then suffered to rise to the point at which the next observations were to be made. The consumption of gas was again carefully adjusted to ·65 cubic foot per hour, when twenty photometrical observations were again made. Similar sets of observations at the remaining higher pressures up to the full atmospheric pressure completed the series.

In the following tabulated results the illuminating power of the standard flame is assumed to be 100, whilst the numbers given in the several columns represent the luminosity of the experimental flame compared with this standard. In all the series of observations, the consumption of gas by the experimental flame was ·65 cubic foot per hour, measured at the atmospheric pressure.

First Series.

No. of Observation.	Illuminating power of Experimental Flame compared with Standard Flame at 100.					
	Pressure of air in receiver=					
	6·6 in. mercury.	9·6 in. mercury.	14·6 in. mercury.	19·9 in. mercury.	24·9 in. mercury.	29·9 in. mercury.
1	1·0	6·4	24·2	63·4	90·2	119·9
2	1·0	6·4	24·4	63·4	90·1	119·6
3	1·1	6·5	24·1	63·1	90·0	119·3
4	1·0	6·5	24·1	63·1	89·8	119·2
5	1·1	6·5	24·1	63·3	90·4	119·5
6	1·2	6·6	24·2	63·1	90·4	119·6
7	1·2	6·5	24·2	63·2	90·2	119·4
8	1·1	6·5	24·4	63·2	90·1	119·6
9	1·2	6·4	24·4	63·4	90·1	119·5
10	1·1	6·5	24·4	63·3	90·0	119·5
11	1·1	6·5	24·1	63·5	89·8	119·7
12	1·2	6·5	24·2	63·5	89·8	119·9
13	1·1	6·6	24·2	63·6	89·7	120·2
14	1·2	6·5	24·4	63·6	89·9	120·5
15	1·1	6·5	24·3	63·8	90·0	120·6
16	1·0	6·5	24·2	64·0	90·0	120·6
17	1·1	6·4	24·1	64·1	89·8	120·7
18	1·1	6·5	24·1	64·0	89·7	120·7
19	1·0	6·5	24·2	63·8	89·9	120·8
20	1·1	6·5	24·1	63·8	90·0	120·6
Mean	1·1	6·5	24·2	63·5	90·0	119·97

Second Series.

No. of Obser-vation.	Illuminating power of Experimental Flame compared with Standard Flame at 100.										
	Pressure of air in receiver =										
	10·2 in. mercury	12·2 in. mercury	14·2 in. mercury	16·2 in. mercury	18·2 in. mercury	20·2 in. mercury	22·2 in. mercury	24·2 in. mercury	26·2 in. mercury	28·2 in. mercury.	30·2 in. mercury.
1	4·3	14·6	23·6	35·1	44·0	56·8	72·9	86·3	95·6	108·1	117·5
2	4·2	14·6	23·7	35·1	44·2	56·8	72·9	86·3	95·5	108·1	117·5
3	4·3	14·6	23·7	35·1	44·2	56·5	72·9	86·3	95·5	108·6	118·4
4	4·3	14·6	23·6	34·9	44·2	56·8	72·9	86·8	95·4	108·6	118·4
5	4·2	15·0	23·6	35·1	44·2	56·5	72·6	86·8	95·1	108·1	118·4
6	4·3	15·0	23·6	34·9	44·2	56·5	72·9	87·1	95·5	109·0	118·4
7	4·2	15·0	23·7	35·1	44·0	56·8	72·6	87·1	95·7	109·0	118·4
8	4·3	15·0	23·7	34·9	44·0	56·8	72·9	87·1	95·9	109·5	118·8
9	4·2	15·0	23·7	34·9	44·2	56·8	73·2	86·8	95·8	109·0	118·8
10	4·3	15·0	23·5	34·7	44·2	57·0	73·2	86·8	95·8	109·5	119·4
11	4·2	14·9	23·5	34·7	44·2	57·0	72·9	86·8	95·9	108·6	119·4
12	4·2	14·9	23·6	34·7	44·4	56·8	72·9	86·8	95·9	108·6	119·4
13	4·3	15·0	23·7	34·9	44·4	56·8	72·9	87·1	95·9	108·1	119·9
14	4·3	15·0	23·6	34·7	44·6	57·0	73·2	87·1	96·0	108·1	119·9
15	4·2	15·0	23·7	34·9	44·6	56·8	72·9	87·1	95·9	108·6	119·4
16	4·2	15·0	23·6	35·1	44·6	57·0	72·2	86·8	95·7	109·0	119·4
17	4·3	15·0	23·5	35·1	44·6	56·8	72·6	87·1	95·7	108·6	118·8
18	4·3	15·0	23·5	34·9	44·4	56·8	72·9	86·8	95·9	108·6	118·4
19	4·3	14·9	23·6	34·9	44·6	57·0	73·2	86·8	95·6	108·1	118·4
20	4·3	15·0	23·5	34·9	44·6	56·8	73·2	87·1	95·9	108·6	117·5
Mean	4·3	14·9	23·6	34·9	44·4	56·8	72·9	86·8	95·7	108·6	118·8

In order to bring the two series of observations into more strict comparison with each other, and with following determinations, it will be convenient to reduce the mean experimental numbers to a standard of illuminating power, in which the light at the maximum pressure, that is the full atmospheric pressure, is assumed to be 100. We then get the following numbers:—

First Series.

Pressure of air in receiver in ins. of mercury.	Mean illuminating power. Experimental.	Mean illuminating power. Reduced.
29·9	119·97	100·0
24·9	90·0	75·0
19·9	63·5	52·9
14·6	24·2	20·2
9·6	6·5	5·4
6·6	1·1	·9

Second Series.

Pressure of air in receiver in ins. of mercury.	Mean illuminating power. Experimental.	Mean illuminating power. Reduced.
30·2	118·8	100·0
28·2	108·6	91·4
26·2	95·7	80·6
24·2	86·8	73·0
22·2	72·9	61·4
20·2	56·8	47·8
18·2	44·4	37·4
16·2	34·9	29·4
14·2	23·6	19·8
12·2	14·9	12·5
10·2	4·3	3·6

These numbers show that even the natural oscillations of atmospheric pressure produce a considerable variation in the amount of light emitted by gas-flames; and as such a variation is of interest from a technical point of view, it appeared to me of sufficient importance to warrant a special series of observations within, or nearly within, the usual fluctuations of the barometrical column. In order to attain greater delicacy in the pressure-readings in these experiments, a water-gauge was substituted for a mercurial one, but its indications are translated into inches of mercury in the following tabulated results:—

Third Series.

No. of Observation.	Illuminating power of Experimental Flame compared with Standard Flame at 100.			
	Pressure of air in receiver=			
	27·2 in. of mercury.	28·2 in. of mercury.	29·2 in. of mercury.	30·2 in. of mercury.
1	70·1	75·5	77·8	83·7
2	70·1	74·5	77·8	84·1
3	70·4	73·8	78·8	84·1
4	70·1	73·8	79·9	83·7
5	70·1	73·8	77·8	83·7
6	70·4	74·2	77·8	83·7
7	70·1	73·8	77·8	83·4
8	70·1	74·2	77·8	83·4
9	70·4	74·5	80·2	83·4
10	70·1	74·5	80·2	83·4
11	70·1	74·8	79·8	83·0
12	70·4	74·8	79·2	83 0
13	70·1	74·5	80·5	82·7
14	70·4	74·8	78·8	83·0
15	70·4	75·5	79·8	82·7
16	70·2	75·5	79·8	83·0
17	70·1	75·5	78·8	83·0
18	70·7	75·5	80·2	83·4
19	70·7	75·5	79·8	83·4
20	70·7	75·1	80·5	83·7
Mean	70·3	74·7	79·2	83·4

Reducing the means of these results, as before, to the maximum standard of 100, we have the following numbers:—

Third Series.

Pressure of air in receiver in ins. of mercury.	Mean illuminating power. Experimental.	Mean illuminating power. Reduced.
30·2	83·4	100·0
29·2	79·2	95·0
28·2	74·7	89·6
27·2	70·3	84·3

It is thus evident that the combustion of an amount of gas which will give a light equal to 100 candles when the barometer stands at 31 inches, will yield light equal only to 84·3 candles when the barometer falls to 28 inches. Such a variation in the luminosity of gas-flames with the oscillations of the barometer will obviously elude the ordinary modes of taking the illuminating power of gas, inasmuch as the standard light with which the gas is compared is also subject to the same influence. Still, although the relative light of gas as compared with candles may remain nearly or quite unaltered, yet its absolute illuminating value depends greatly upon the height of the barometer at the place where it is burnt. Thus a quantity of coal-gas which in London would yield a light equal to 100 candles would, if burnt in Munich, give an illuminating effect equal to little more than 91 candles; whilst if used to light the city of Mexico, its luminosity would be reduced to 61·5 candles. These numbers are independent of the change of volume by reduced pressure. If equal volumes of the same sample of coal-gas were consumed in London and Mexico, the illuminating effects would be as 100 : 46·2, the temperature being the same in both cases.

An inspection of the above three series of observations, reveals the fact that the rarefaction of air, from atmospheric pressure downwards, produces a uniform diminution of light until the pressure is reduced to about 14 inches of mercury, below which the diminution of illuminating power proceeds at a less rapid rate. This uniformity of relation between pressure and luminosity will be more clearly seen from Plate XIX. diagrams 1 and 2, in which the luminosity is represented by the ordinates, and the pressure by the abscissæ measured from the origin B. If therefore the luminosity were simply proportional to the pressure, the curve of luminosity would coincide with the diagonal drawn from A to B in diagram No 1. Inasmuch, however, as the diminution of light is more rapid than the diminution of pressure, the lines A C and A D, representing the experimental results of the first and second series of observations, fall between this diagonal and the ordinate corresponding to the point A. Diagram No. 2 shows the results of the third series of observations: in order to render it as open as possible, only that portion of the square is given through which the experimental line A B passes. The line A C in diagram No. 1 represents the average results of the first series of observations, whilst A D indicates those of the second series. It will be seen, from an inspection of both

series, not only that the lines are nearly coincident, but that they do not, down to 14 inches pressure, deviate much from a straight path. This is obviously due to an equal, or nearly equal diminution of light for each equal decrement of pressure down to about 14 inches, below which pressure both lines deviate markedly from their previous direction, indicating an alteration in the rate of the diminution of luminosity. The mean results of the three series of observations give approximately 5·1 per cent. of the luminosity at 30 inches pressure as the diminution of light corresponding to each diminution of 1 inch of mercurial pressure down to 14 inches. The following Tables exhibit the illuminating effect actually observed compared with that calculated from this constant:—

First Series.

Pressure in inches of mercury.	Illuminating power.	
	Observed.	Calculated.
29·9	100	100
24·9	75·0	74·5
19·9	52·9	49·0
14·6	20·2	22·0
9·6	5·4	− 3·5
6·6	·9	−18·8
Second Series.		
30·2	100·	100
28·2	91·4	89·8
26·2	80·6	79·6
24·2	73·0	69·4
22·2	61·4	59·2
20·2	47·8	49·0
18·2	37·4	38·8
16·2	29·4	28·6
14·2	19·8	18·4
12·2	12·5	8·2
10·2	3·6	−2·0
Third Series.		
30·2	100	100
29·2	95·0	94·9
28·2	89·7	89·8
27·2	84·4	84·7

The dotted lines in diagrams Nos. 1 and 2 represent the calculated luminosity according to the above Tables. The experimental lines above 14 inches pressure do not in any part of their course deviate more from the calculated line than might be expected from the usual errors of experiment. The law of the diminution of the light of gas-flames by reduction of pressure from 30 inches to 14 inches of mercury, may therefore be thus stated. *Of* 100 *units of light emitted by a gas-flame burning in air at a pressure of* 30 *inches of mercury,* 5·1 *units are extinguished by each diminution of one mercurial inch*

of atmospheric pressure; or, more generally, *the diminution in illuminating power is directly proportional to the diminution in atmospheric pressure.*

It must, however, here be remarked that the above determinations only establish the constant 5·1 for the particular quality of gas with which the experiments were performed. It still remained to be ascertained whether a flame from gas of a different quality would be amenable to the same rate of reduction; a fourth series of observations was therefore made with gas naphthalized to such an extent as nearly to double its illuminating power. The consumption of gas by the experimental flame was, as before, ·65 cubic foot per hour. The following results were obtained:—

Fourth Series.

No. of Observation.	Illuminating power of Experimental Flame compared with Standard Flame at 100.					
	Pressure of air in receiver=					
	6·9 in. mercury.	9·9 in. mercury.	14·9 in. mercury.	19·9 in. mercury.	24·9 in. mercury.	29·9 in. mercury.
1	1·0	7·3	28·0	55·6	85·3	114·0
2	1·0	7·2	28·0	55·5	85·2	114·0
3	1·1	7·2	28·1	55·6	85·2	114·1
4	1·0	7·3	28·2	55·6	85·3	114·2
5	1·0	7·5	28·1	55·8	85·3	114·5
6	·9	7·5	28·1	55·9	85·5	114·6
7	·9	7·2	28·2	55·8	85·6	114·8
8	1·0	7·2	28·2	55·7	85·6	114·9
9	·9	7·2	28·1	55·9	85·5	115·1
10	1·0	7·3	28·2	55·9	85·7	115·2
11	1·1	7·4	28·3	55·5	85·4	115·2
12	1·1	7·5	28·3	55·4	85·3	115·3
13	·9	7·5	28·3	55·5	85·7	115·5
14	·9	7·6	28·5	55·2	85·7	115·4
15	·9	7·5	28·3	55·3	85·5	115·4
16	1·0	7·6	28·3	55·1	85·9	115·5
17	1·0	7·6	28·4	55·2	86·0	115·5
18	1·1	7·5	28·4	55·3	86·0	115·4
19	1·1	7·5	28·5	55·3	86·0	115·2
20	1·1	7·6	28·3	55·7	85·6	115·2
Mean	1·00	7·42	28·24	55·54	85·58	114·95

The following Table, calculated from the above, shows that these results are completely in harmony with those obtained with unnaphthalized gas, thus proving that the rate of diminution of luminosity in rarefied air is the same for all hydrocarbon gases, of whatsoever quality; the two last columns being nearly identical down to 14·9 inches pressure.

Pressure of air in inches of mercury.	Mean illuminating power. Experimental.	Mean illuminating power. Reduced.	Illuminating power. Calculated.
29·9	114·95	100	100
24·9	85·58	74·4	74·5
19·9	55·54	48·3	49·0
14·9	28·24	24·5	23·5
9·9	7·42	6·4	− 2·0
6·9	1·02	·9	−17·3

This series was continued down to 4·6 inches pressure, but the illuminating power of the flame could then no longer be measured by the photometer.

β. *Influence of Compression.*

The foregoing experiments having demonstrated a very remarkable diminution of light in candle- and gas-flames by a reduction of atmospheric pressure, it became interesting to ascertain the effect of compressed air upon the luminosity of similar flames. At the very outset of this part of the inquiry considerable difficulties presented themselves, since it became necessary to abandon a gaseous combustible, which could not be compressed to the necessary degree, and then delivered at a uniform pressure through a burner, without very complex apparatus. I was thus compelled to resort to solid or liquid combustibles, the irregularities of which were still further increased by the space within the combustion-chamber being necessarily more confined, in order that its walls might the better sustain high pressures. These difficulties in the way of accurate determinations were, however, by no means the most formidable; for it was soon found that any considerable increase of atmospheric pressure caused both candle- and oil-flames to throw off large quantities of fuliginous matter, the formation of which could not be prevented by any amount of draught that could be established in the chimney of the apparatus. Hence, although the luminosity of the flames was greatly increased, yet it was obviously much less so than would have been the case under conditions of more perfect combustion. In fact it soon became evident that the determinations of increase of luminosity by compression must be made in a manner precisely the reverse of that employed for the corresponding determinations in rarefied air; for whilst in the latter case the experiments were made with flames, which at ordinary atmospheric pressure were saturated with carbon particles, in the former it was found necessary to commence with flames which were very feebly, or not at all luminous at common pressures. Such is the effect of compressed air in determining the precipitation of carbon particles within the flame, that a small alcohol lamp, which at the ordinary pressure burnt with a pure blue flame, became highly luminous when placed under a pressure of four atmospheres; and it can scarcely be doubted that at a pressure of five or six atmospheres, its luminosity would be equal to that of sperm oil burning at atmospheric pressure.

The apparatus employed, and which is shown in Plate XVIII. fig. 2, was very similar to that used in the previous part of the inquiry. A is the gas-governor regulating the supply to the standard flame B. H H is the photometer arranged as before, and *a a* are the ground plates, rods, and screws for securely closing the ends of the glass cylinder containing the experimental flame. The comparatively thin and wide cylinder used in the rarefaction experiments was here replaced by the strong glass cylinder D, 12 inches long, 2 inches internal diameter, and $\frac{5}{8}$ inch thick; *e* is the lamp furnishing the experimental flame; it is fixed upon the rod *l* passing through a stuffing-box in the lower plate, and enabling it to be adjusted to any height. *b* and *c* are the glass chimney and stopcock arranged as before, except that *c* now opens at once into the air. The

interior of D is connected with the pressure-gauge G by the tube *i*, whilst the cock *d* communicates with the compressed-air reservoir F by means of the tube *f*. E is a condensing syringe communicating with F by the tube *k*. By this interposition of the reservoir F, a very constant pressure could easily be maintained in the cylinder D.

The experiments were made in the following manner. The cover *a* being removed, and F charged with compressed air, a gentle stream of the latter was turned into D through the cock *d*. The lamp *e* was now lighted and the cover *a* firmly screwed into its place, the cock *c* being wide open. The admission of air through *d* was then regulated so as to produce in the chimney *b* that degree of draught necessary for obtaining the maximum amount of light in the experimental flame. After the latter had been allowed to burn for about half an hour, so as to bring the surrounding glass to a temperature which afterwards remained tolerably uniform, a series of photometrical observations were made. The egress of air through the cock *c* was then gradually diminished, whilst *d* was fully opened, so as to establish a free communication, and consequently an equality of pressure, between the reservoir F and the cylinder D. The pressure, as indicated by the gauge G, was now adjusted, by the more or less rapid working of the pump E, to that required for the next series of observations. In practice it was found impossible, with the same liquid in the lamp, to extend any series of observations over a greater range than one atmosphere, owing to the experimental flame beginning to smoke at the higher pressure, if it possessed a measurable illuminating power at the lower one.

Owing to the difficulties above mentioned, I have only been able to obtain satisfactory determinations between one and two atmospheres. In these determinations the lamp was supplied with amylic alcohol—a liquid which, whilst affording an appreciable amount of light in the experimental flame under one-atmosphere pressure, was found to burn under two atmospheres without smoke, although at a somewhat higher pressure it began to evolve unconsumed carbon. The following results were obtained:—

No. of Observation.	Illuminating power of Experimental Flame compared with Standard Flame at 100. Pressure in receiver in inches of mercury =		
	29·7 inches.	59·7 inches.	59·5 inches.
1	21·0	55·6	55·3
2	21·0	56·2	55·4
3	21·2	56·3	55·3
4	21·1	56·3	55·4
5	21·2	56·1	55·4
6	21·1	56·0	55·3
7	21·2	56·0	55·4
8	21·5	55·9	55·5
9	21·6	55·6	55·5
10	21·6	55·4	55·5
11	21·0	55·4	55·3
Mean	21·2	55·9	55·4

These numbers approximate to those calculated in accordance with the law already given for pressures below that of the atmosphere, thus confirming that law for pressures up to two atmospheres, as is seen from the following comparison, in which the experimental numbers are reduced to the standard of 100 at atmospheric pressure.

Pressure.	Illuminating power.	
	Observed.	Calculated.
1 Atmosphere	100	100
2 Atmospheres first ..	263·7	253
2 Atmospheres second	261·3	253

Further determinations, in which the illuminating power at three- and four-atmospheres pressure was compared, yielded results differing widely from this law, and indicating a much more rapid increase of light; but as the liability to errors of observation increases greatly at these higher pressures, I place very little confidence in the numbers obtained, which I will nevertheless here briefly state in the same form as the last Table. In these experiments the lamp was fed with a mixture of five parts of vinic alcohol and one part of amylic alcohol. The lamp when fed with this mixture had no appreciable illuminating effect under ordinary atmospheric pressure.

Pressure.	Illuminating power.	
	Observed.	Calculated.
3 Atmospheres	406	406
4 Atmospheres	959	559

In endeavouring to trace the causes of this variation of luminosity, it will be convenient first to consider the general conditions upon which the light of flames depends. The luminosity of the flames generally used for artificial light emanates from two sources; viz., first, from the ignition of minute particles of carbon floating in the shell of flame; and secondly, from the incandescence of gaseous matters. The latter source of illumination probably does not usually furnish more than one per cent. of the total amount of light; consequently nearly the whole of the light given out by flames under ordinary circumstances is due, as DAVY first pointed out*, to the ignition of solid carbonaceous matter. The light emitted by incandescent gaseous particles becomes, however, much more prominent at very low pressures; and as this light is not materially influenced by pressure, it causes the deviation from the law of diminution of light, seen at the lower extremities of the lines A C and A D in Plate XIX. diagram No. 1. In order to gain a clear conception of the mechanism of a candle- or gas-flame, we must picture to ourselves first a core of gas or vapour containing hydrocarbons, and secondly a shell

* Philosophical Transactions, 1817, p. 64.

of ignited matter closely surrounded on its outside by atmospheric air. The uninterrupted supply of gas or vapour to the core forces the contents of the latter constantly through the ignited shell, at the inner wall of which, those hydrocarbons that cannot exist at a bright red heat, either undergo decomposition into light carburetted hydrogen and free carbon, or imperfect combustionin to water, carbonic oxide, and free carbon, or finally perfect combustion into water and carbonic oxide, or even carbonic acid, without any separation of free carbon. The nature of the decomposition or combustion which these hydrocarbons undergo on coming in contact with the ignited shell, thus evidently depends upon the amount of oxygen which gains access to the interior of the shell; if that quantity be insufficient to convert the whole of the carbon of the hydrocarbons into carbonic oxide, the residue will be precipitated, and the flame will be a more or less luminous one; whilst if the amount of oxygen present be sufficient, after burning the hydrogen, to consume the whole of the carbon to carbonic acid or even to carbonic oxide, no light will be produced from the incandescence of carbon particles.

Now it is well known that the light of any flame may be increased by increasing the number of carbon particles simultaneously floating in it, provided those particles are consumed before they leave the flame, and are not evolved as smoke. I have also elsewhere shown* that the light of gas-flames, and doubtless that of candles and oil also, greatly depends upon the heat of the flame, the rise in temperature caused by merely heating the air supplied to a gas-lamp, by the waste heat of the flame itself, being sufficient to increase the light to the extent of 67 per cent. without any increased consumption of gas. Such being the conditions necessary for the *increase of light*, it is scarcely necessary to add that the reversal of these conditions, viz. the decrease in the number of particles of carbon existing in the flame at a given time, imperfect combustion allowing the escape of unconsumed carbon, and decrease of temperature in the flame, determine a *diminished luminosity*.

One of the first causes which naturally suggests itself to account for the diminution of light by decreased atmospheric pressure, is the diminished amount of oxygen in a given bulk of the supporting medium rendering combustion imperfect, and thus either causing particles of carbon to escape unconsumed, or determining their conversion into carbonic oxide instead of carbonic acid. The effect of the first would be to diminish the luminosity, whilst the second would have the effect of decreasing the light indirectly by diminishing the temperature of the flame. A careful inspection of a gas- or candle-flame, burning in an atmosphere undergoing gradual rarefaction, does not afford the slightest evidence of smoke, or even of an increased tendency to throw off fuliginous matter; on the contrary, the tendency to smoke obviously diminishes as the rarefaction progresses; whilst, on the other hand, the fact that an increase of pressure beyond that of the atmosphere causes the most smokeless flames to become smoky, renders utterly untenable the assumption that the escape of unconsumed carbon is one of the causes of diminished luminosity in rarefied atmospheres. Whether or not there is imperfect combustion in

* URE's Dictionary, 1860, article "Coal-gas."

the sense of an escape of carbonic oxide instead of carbonic acid from the flame, could not be thus decided, and demanded a closer investigation.

To determine this point I collected samples of the gases escaping from the chimney *b* (fig. 1) of the experimental flame (which in this case was that of a sperm candle) when burning under atmospheric pressure, and again when burning under a pressure of only 8 inches of mercury. These gases were first treated with caustic potash to absorb carbonic acid; they were then exploded with an equal volume of electrolytic water-gas, and subsequently with excess of hydrogen. The explosion with water-gas caused no contraction, proving the absence of carbonic oxide. The following numbers were obtained:—

I. Gases from candle burning at atmospheric pressure:—

	Volume of gas.	Temperature.
Gas used	256·0	7·0° C.
After absorption of carbonic acid	238·1	7·0 „
After explosion with electrolytic gas	238·0	7·0 „
After admission of hydrogen	373·7	7·0 „
After explosion	283·6	7·0 „

II. Gases from candle burning at 8 inches mercurial pressure:—

	Volume of gas.	Temperature.
Gas used	290·8	7·1° C.
After absorption of carbonic acid	267·2	7·1 „
After explosion with electrolytic gas	267·3	7·1 „
After admission of hydrogen	457·8	7·1 „
After explosion	367·9	7·1 „

These numbers give the following per-centage composition of the two samples of gas:—

	I.	II.
Nitrogen	81·28	81·58
Oxygen	11·73	10·30
Carbonic acid	6·99	8·12
Carbonic oxide	0·00	0·00
	100·00	100·00

These results prove that in both cases there was no escape of unconsumed combustible gas; consequently *the diminution of light in rarefied atmospheres is not due to imperfect combustion in any form.*

Taken in connexion with the experiments in compressed air, in which imperfect combustion attended with the evolution of fuliginous matter was very marked, these data lead to the remarkable conclusion that *the compression of air renders the combustion of gaseous matter less perfect*; and that, within certain limits at least, *the more rarefied the atmosphere in which flame burns, the more complete is its combustion.* Thus it is evident, not only that no diminution of light can arise from imperfect combustion in rarefied

atmospheres, but also that no reduction of temperature in the flame can occur from the same cause.

A second cause of the diminution of the light of combustion in rarefied atmospheres, and its increase in compressed ones, might be sought for in a possible difference between the temperatures of the flame in the two cases. It is well known that if air be allowed to escape from a vessel into a vacuum, a considerable diminution of temperature ensues in the vessel from which the air escapes; and inasmuch as the gaseous products of combustion assume a larger volume in rarefied atmospheres than in compressed ones, it can scarcely be doubted that the pyrometric thermal effect of a flame must be diminished to some extent by rarefying the medium in which it burns; nevertheless this effect may be nearly or quite neutralized by the smaller amount of refrigeration caused by the rarefied atmosphere. In order to elucidate this point, a spiral of platinum wire was ignited to visible redness in a flame of hydrogen; on then rarefying the air around the flame and wire, no appreciable alteration in the temperature of the platinum spiral could be noticed. A similar experiment was tried with an alcohol flame, and with the same result. A spiral of platinum wire placed under the receiver of an air-pump, was ignited to visible redness by a voltaic current; on exhausting the receiver, the glow of the platinum gradually increased nearly to whiteness. On readmitting the air, it again diminished to dull redness, showing that the refrigerating effect of rarefied air is much less than that of air at the ordinary pressure. Thus, whilst the temperature produced within a given flame is lowered by rarefaction, the escape of heat from its exterior is hindered by the same process,—the result apparently being that the actual temperature of the flame undergoes but little alteration. This confirms DAVY's conclusion, that *rarefaction and compression, within certain limits at least, do not exert any considerable influence upon the heat of flame.*

Although an inquiry into two of the possible causes of the diminution of the light of combustion in rarefied atmospheres has thus failed to afford any explanation of the phenomenon, yet one of them indirectly points to what I believe to be the conditions determining the variation in illuminating power. If it be true that combustion is more complete in rare atmospheres than in dense ones, it follows that the light of a smokeless flame must decrease with a diminution of pressure, since, with more perfect combustion, that is, with freer access of oxygen to every part of the flame, there must be a diminution of unconsumed carbon separated within the flame, and consequently a diminished amount of light evolved. In fact, the appearance of the experimental flame during the progress of rarefaction on the one hand, and of compression on the other, can scarcely leave a doubt on the mind of an observer, that the variation of luminosity depends essentially upon the admission of oxygen to that portion of the shell of flame where particles of carbon are usually precipitated, and where consequently the region of luminosity is situated. That an admission of oxygen or air to the interior of a luminous flame has the effect of greatly diminishing or even practically annihilating its luminosity, has been long known

and even utilized in the wire-gauze and BUNSEN'S burners, where heat and not light is the object of the combustion of gas. But it may be asked, what conditions are there in the combustion of flame in rarefied air, that favour the admission of a larger proportion than usual of air to the interior of the flame? In reply, it may be stated that there are two conditions in such combustion, both of which directly tend to produce this result. The first of these conditions, and the one to which I conceive nearly the whole of the effect to be due, is the greater mobility of *rarefied* gaseous bodies, which must produce a more rapid admixture of the flame, gases, and external air than would otherwise take place. The second condition is the gradual, though slow, increase in the volume of the flame as the atmospheric pressure decreases, thus causing the flame to present a gradually increasing surface of contact with the exterior air. This alteration in the volume of flame by diminished pressure is more strikingly seen with a sperm candle than with gas. When such a candle burns under a pressure of two atmospheres, its flame presents the appearance of a sharp spike scarcely one-fourth of an inch in diameter at its lower and broadest part, the apex being lost in the dense smoke which issues from the upper portion of the flame. If the pressure be now diminished, the diameter of the spike markedly increases, especially about its centre, until at one-atmosphere pressure the flame assumes its ordinary appearance. On now rarefying the air, the transverse diameter of the flame goes on increasing until, when the pressure is reduced to about 6 mercurial inches, the flame becomes nearly globular with a diameter of about three-fourths of an inch.

Now, as the amount of combustible matter in the flame was maintained constant in the photometrical experiments detailed above, it follows that the increased external flame surface must so alter the conditions of combustion as to bring the constant amount of combustible matter into contact with a gradually increasing quantity of oxygen. That a large amount of air does, even under ordinary circumstances, gain access to the interior of gas- and candle-flames, has been proved by the interesting researches upon the gases of these flames recently made by HILGARD*, who found 64 per cent. of nitrogen in the interior of a candle-flame, and by LANDOLT†, who detected 66 per cent. of nitrogen in the interior of a gas-flame; on no occasion, however, did these experimenters find oxygen in the luminous portion of the flame, although it was found in the blue or non-luminous section. I conceive therefore that these consequences of diminished pressure, viz. increased gaseous mobility and augmented volume of flame, are quite competent to explain the variations in luminosity resulting from alterations in the pressure of the supporting medium, and that *these variations in illuminating power depend chiefly, if not entirely, upon the ready access or comparative exclusion of atmospheric oxygen as regards the interior of the flame.*

In conclusion, the influence of atmospheric pressure upon the phenomena of combustion may be thus summed up.

* Ann. der Chem. und Pharm. vol. xcii. p. 129. † POGGENDORFF'S 'Annalen,' vol. xcix. p. 389.

1. The rate of burning of candles and other similar combustibles, whose flames depend upon the volatilization and ignition of combustible matter in contact with atmospheric air, is not perceptibly affected by the pressure of the supporting medium.

2. The rate of burning of self-supporting combustibles, like time-fuses, depends upon the rapidity of fusion of the combustible composition, which rapidity of fusion is diminished by the more rapid removal of the heated gases from the surface of the composition. Hence the rate of burning of combustibles of this class depends upon the pressure of the medium in which they are consumed. In the case of time-fuses, the increments in the time of burning are proportional to the decrements in the pressure of the surrounding medium.

3. The luminosity of ordinary flames depends upon the pressure of the supporting medium; and, between certain limits, the diminution in illuminating power is directly proportional to the diminution in atmospheric pressure.

4. The variation in the illuminating power of flame by alterations in the pressure of the supporting medium depends chiefly, if not entirely, upon the ready access of atmospheric oxygen to, or its comparative exclusion from, the interior of the flame.

5. Down to a certain minumum limit, the more rarefied the atmosphere in which flame burns, the more perfect is its combustion.

Fig: 1.

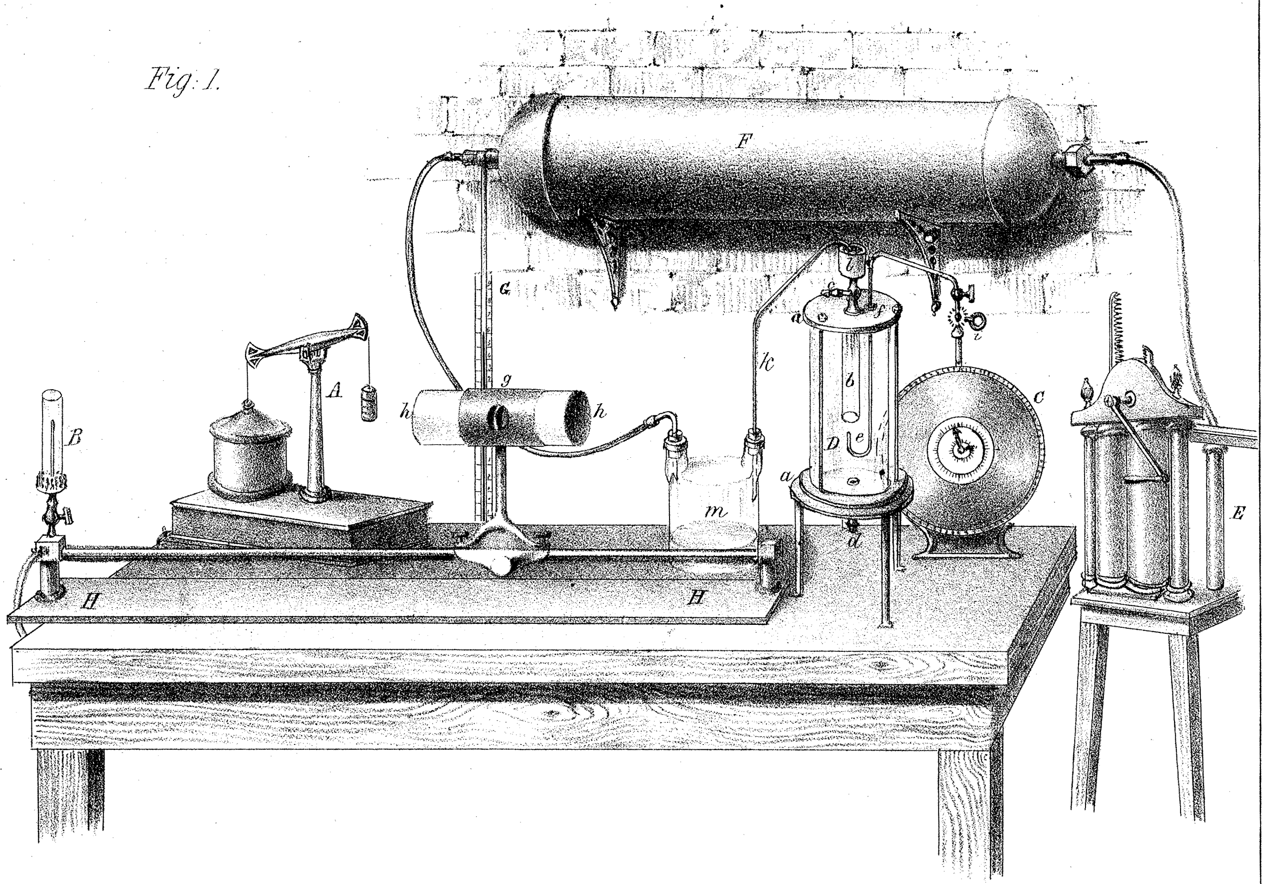
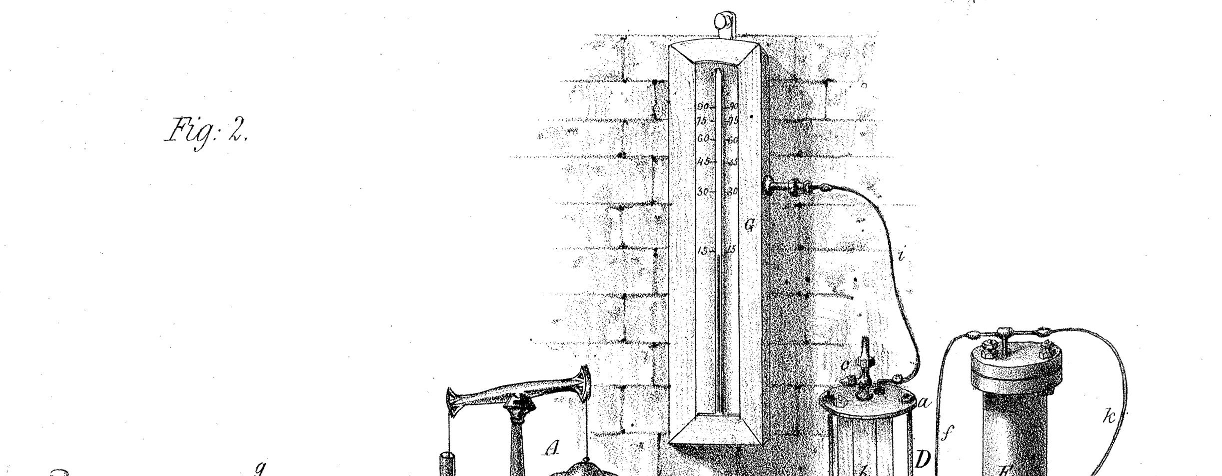


Fig: 2.



J. Basire lith.

Diagram Nº I.

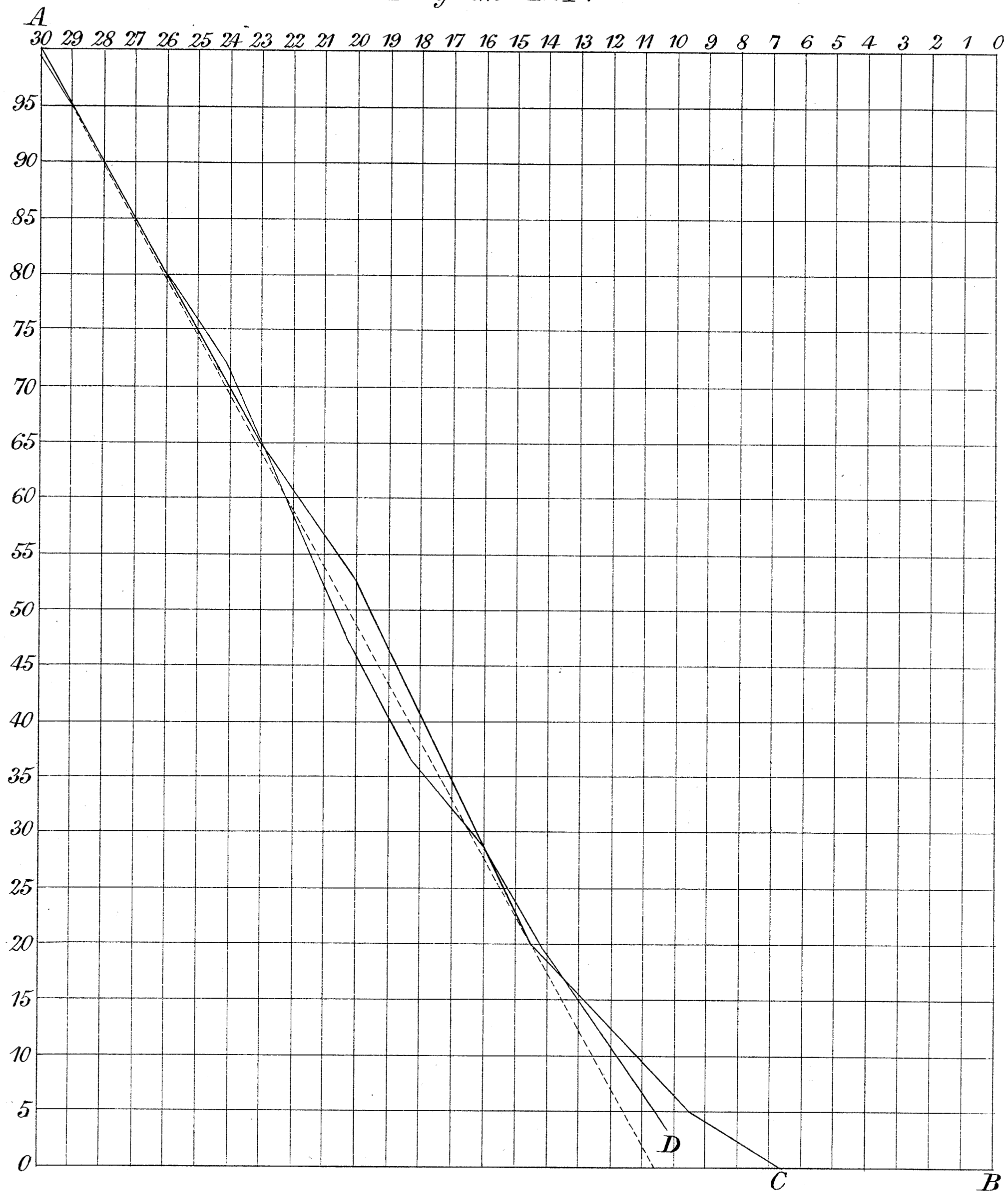
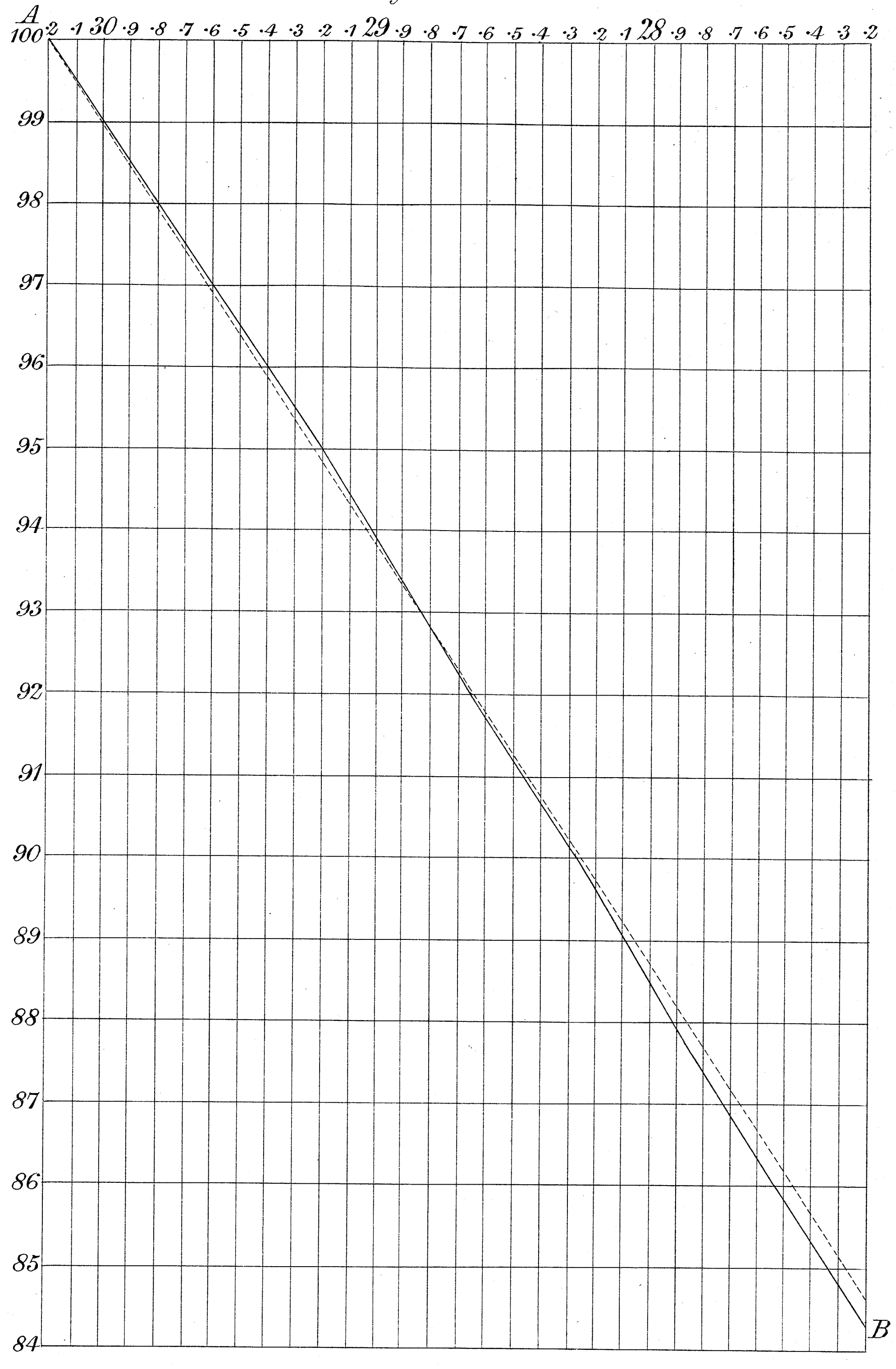


Diagram Nº II.



J. Basire, lith.